

Exceptional point induced robust unidirectional guided resonance in perturbed silicon nanogratings

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Received 14 May 2026; revised 5 June 2026; accepted 15 June 2026; posted 18 June 2026; published 29 June 2026

Unidirectional guided resonances (UGRs) enable static unidirectional radiation of eigenstates and have been widely studied. Exceptional points (EPs) in non-Hermitian open systems provide a unique perspective for exploring UGRs. However, existing studies mainly focus on the topological properties of UGRs, while how the region delimited by an EP affects the radiation behavior of UGRs remains unclear. Here, we investigate the radiation of EP-related UGRs in a notch-perturbed silicon nanograting. At notch parameters $\Delta = 0.3$ and $\delta = 0.045$, the complex eigenfrequencies of two modes coalesce to form an EP. In the region delimited by the EP, where the imaginary parts remain nearly degenerate, a UGR with an asymmetric radiation ratio η of 41 dB appears. The radiative losses of the modes remain close in this region, allowing η to remain high under structural perturbations of the grating and variations in the ambient refractive index n_2 . Further tuning of the notch parameters shows that changes in interband coupling drive the UGR to migrate on the same band toward the critical interband coupling state associated with the EP. These results indicate that the region delimited by the EP improves the geometrical tolerance of UGRs and provides a route to designing devices with robust unidirectional radiation. © 2026 Optica Publishing Group. All rights, including for text and data mining (TDM), Artificial Intelligence (AI) training, and similar technologies, are reserved.

<https://doi.org/10.1364/OL.605330>

Unidirectional guided resonances (UGRs) in photonic crystal slabs offer an intrinsic route to unidirectional radiation without external reflectors [1,2]. Existing studies on UGRs mainly follow two routes. The topological perspective links UGRs to polarization singularities in momentum space [3–8], including circular polarization points (C points) arising from the splitting of bound states in the continuum (BICs) [9–12], vacuum singularities [13], and singularities associated with exceptional points (EPs) [14,15]. This route usually requires tracking the evolution of polarization singularities and mainly focuses on a single band. By contrast, the mode interaction route realizes UGRs when one radiation channel satisfies the destructive interference

condition [16], making it suitable for analyzing UGRs in multi-mode systems under continuous parameter tuning.

Mode interactions in open radiative systems can be described by eigenmodes with complex eigenfrequencies, whose imaginary parts are related to radiative losses [17,18]. In non-Hermitian systems, an EP is a topological branch point [19,20] where the eigenvalues and eigenstates of two modes coalesce [21], marking a transition in the complex band structure: the real parts are degenerate, and the imaginary parts are split on one side, while the real parts are split and the imaginary parts are degenerate on the other. Previous studies have shown that EPs and UGRs can coexist in parameter space, but the effect of EPs on UGRs remains unclear [16]. Another study used EPs from Dirac point splitting to explain the formation of C points and UGRs, but did not address UGR stability under parameter perturbations [22]. Scattering EPs have been used to realize unidirectional reflectionlessness and absorption asymmetry [23]. Together, these studies relate EPs to UGRs, but how the region delimited by the EP stabilizes UGR radiation channels beyond isolated, perturbation-sensitive momentum space points remains an open question.

Here, we investigate the relation between UGRs and EPs in perturbed silicon nanograting through interband coupling introduced by structural symmetry breaking. The perturbation couples the bound and radiative modes and redistributes the upward and downward radiation channels. A UGR and an EP coexist on the TE_1 band at $\Delta = 0.3$ and $\delta = 0.045$. The EP occurs at $k_x = \pm 0.104$, while the UGR lies in the region delimited by the EP, where the real parts are split, and the imaginary parts are degenerate. In this region, close radiative losses allow the UGR destructive interference condition to persist under parameter perturbations. Thus, the UGR is not limited to an isolated momentum space point, but remains robust to variations in the notch width parameter Δ and the ambient refractive index n_2 . Further tuning Δ at $\delta = 0.05$ shows that the UGR migrates along the TE_1 band through the EP-associated critical position at $\Delta = 0.335$ and $k_x = \pm 0.107$, revealing that the UGR migration path is closely related to the EP distribution. By linking this region, delimited by the EP, to the radiation channel distribution, this work identifies the origin of the enhanced geometrical tolerance

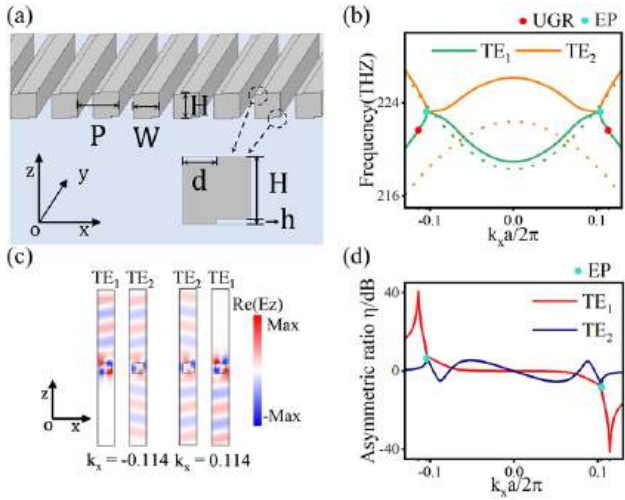


Fig. 1. (a) Silicon nanograting structure with broken mirror symmetries and preserved inversion symmetry. (b) Two TE modes supported by the structure: TE₁ (green) and TE₂ (orange). Dashed lines: uncoupled modes, solid lines: hybridized modes. (c) Electric-field distributions of the UGR at $k_x = \pm 0.114$. (d) The asymmetric radiation ratio η of the two modes. Parameters: $\Delta = 0.3$, $\delta = 0.045$.

of UGRs and supports the design of unidirectional radiation devices with improved tolerance.

The silicon nanograting structure considered in this work is illustrated in Fig. 1(a). The grating has period P , width W , and height H , with $n_1 = 3.48$ for silicon; $n_2 = 1.46$ for the background. Two notches with width d and height h are introduced on opposite sides of the grating with $\Delta = d/P$ and $\delta = h/H$. These notches break the mirror symmetries while preserving inversion symmetry. By tuning Δ and δ , interband coupling is introduced between the symmetry protected bound mode and the radiative mode. This coupling splits the two modes near the original band crossing and redistributes the upward and downward radiation channels. Figure 1(b) shows the band structures of TE₁ and TE₂, represented by the green and orange curves, respectively. The dashed curves denote the uncoupled bands, whereas the solid curves denote the hybridized bands after interband coupling.

When $\Delta = 0.3$ and $\delta = 0.045$, an EP and a UGR coexist on the hybridized TE bands. The cyan dots in Fig. 1(b) mark the EPs formed by the non-Hermitian degeneracy of the two modes. The UGR appears on the TE₁ band at $k_x = \pm 0.114$, and its electric field distribution is shown in Fig. 1(c). Figure 1(d) presents the asymmetric radiation ratio $\eta = \gamma_u/\gamma_d$ [8], where γ_u and γ_d are the upward and downward radiative decay rates. At $k_x = \pm 0.114$, $|\eta|$ reaches 41 dB, indicating strong radiation suppression in one channel. The corresponding radiative decay rates and radiative quality factors $Q_r = \omega/\gamma$ [24] are shown in Figs. 2(a) and 2(b). In far field momentum space, Figs. 2(c) and 2(d) show that this UGR corresponds to a vortex polarization singularity [25,26].

Notably, at $\Delta = 0.3$ and $\delta = 0.045$, a UGR and an EP appear on the hybridized TE bands. At $k_x = -0.104$, the complex eigenfrequencies and eigenstates of the two modes coalesce to form an EP. Figures 3(a) and 3(b) show the real and imaginary parts of the complex band structure in the (Δ, k_x) parameter space for $k_y = 0$ and $\delta = 0.045$, while Figs. 3(c) and 3(d) give the corresponding eigenfrequencies on the negative k_x side. The EP marks the transition from a regime with degenerate real parts and split imaginary parts to one with split real parts and nearly

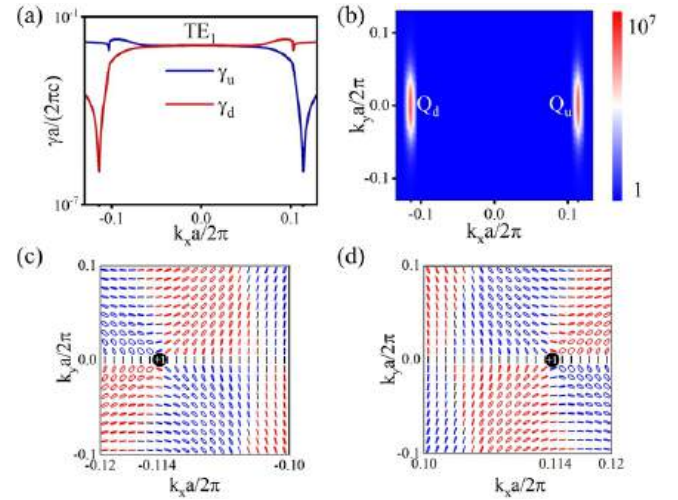


Fig. 2. (a) Upward (γ_u) and downward (γ_d) radiative decay rates of the UGRs on the TE₁ band at $\Delta = 0.3$, $\delta = 0.045$. (b) Q_r of upward and downward radiation channels. (c), (d) Far field polarization states of the downward and upward radiation channels. Red (blue) denotes right-handed (left-handed) circular polarization, and black denotes linear polarization.

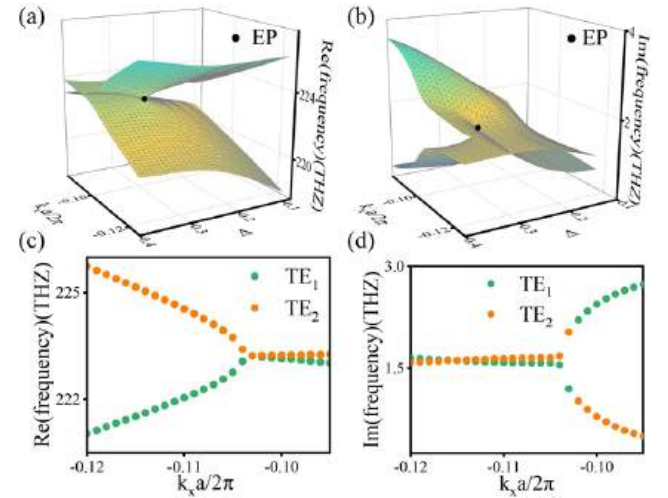


Fig. 3. (a), (b) Three dimensional complex band structures of hybridized modes in the (Δ, k_x) parameter space with $k_y = 0$ at fixed $\delta = 0.045$. Black dots: EP positions. (c), (d) Detailed views of the real and imaginary parts of the complex bands near the EP.

degenerate imaginary parts. The UGR appears in the latter region, where the radiative losses of the two hybridized modes remain close over a finite parameter range.

To describe EP and UGR formation during interband coupling, the two uncoupled complex eigenfrequencies are defined as

$$\omega_{\text{eig}1,2} = \omega_{1,2} - i\Gamma_{1,2}, \quad (1)$$

where ω_j and Γ_j are the eigenfrequency and radiative loss of mode j , respectively. K_{12} and K_{21} denote the interband coupling strengths between the two modes. The effective Hamiltonian is expressed as [27,28]

$$H_{\text{eff}} = \begin{pmatrix} \omega_{\text{eig}1} & K_{12} \\ K_{21} & \omega_{\text{eig}2} \end{pmatrix}. \quad (2)$$

The coupled complex eigenfrequencies are obtained as

$$\omega_{\text{eig}\pm} = \omega_0 - i\Gamma_0 \pm q, q = \sqrt{K_{12}K_{21} + \frac{(\Delta\omega - i\Delta\Gamma)^2}{4}}, \quad (3)$$

where $\Delta\omega = \omega_1 - \omega_2$, $\Delta\Gamma = \Gamma_1 - \Gamma_2$, $\omega_0 = (\omega_1 + \omega_2)/2$, and $\Gamma_0 = (\Gamma_1 + \Gamma_2)/2$. When $q = 0$, the two complex eigenfrequencies and eigenstates coalesce simultaneously, and the EP appears.

The hybridized eigenstates are expressed as

$$\phi_{\pm} = a_{\pm}\phi_1 + b_{\pm}\phi_2, \quad (4)$$

where $a_{\pm}$ and $b_{\pm}$ are the expansion coefficients of the two basis modes. From the eigenvector equation of H_{eff} , the modal amplitude ratio is obtained as

$$\frac{b_{\pm}}{a_{\pm}} = \frac{\omega_{\text{eig}\pm} - \omega_{\text{eig}1}}{K_{12}} = \frac{-(\Delta\omega - i\Delta\Gamma)/2 \pm q}{K_{12}}. \quad (5)$$

The far field radiation amplitudes in the upward and downward radiation channels are written as [16]

$$s_{\sigma,\pm} = d_{\sigma 1}a_{\pm} + d_{\sigma 2}b_{\pm}, \sigma = u, d. \quad (6)$$

Here, d_{u1} , d_{u2} , d_{d1} , and d_{d2} are the coupling coefficients from the two modes to the upward and downward radiation channels. Therefore, the destructive interference condition for a UGR is

$$d_{\sigma 1}K_{12} + d_{\sigma 2} \left[-\frac{\Delta\omega - i\Delta\Gamma}{2} \pm q \right] = 0. \quad (7)$$

From Eq. (3), the radiative loss mismatch between the two hybridized modes is $|\Gamma_+ - \Gamma_-| = 2|\text{Im}(q)|$. In the region delimited by the EP, q is nearly real, so the real parts of the two hybridized modes are split while the imaginary parts remain nearly degenerate. This small radiative loss mismatch helps maintain the modal amplitude balance required by Eq. (7). Therefore, interband coupling regulates both the complex band structure and the radiation channel distribution, providing a common framework to discuss the coexistence of EP and UGR.

To examine whether the region delimited by the EP supports UGR stability, we scan the notch parameters Δ and δ together. Figure 4(a) shows the maximum asymmetric radiation ratio η in the two dimensional (Δ, δ) parameter space, where circles mark the projected EP positions. At $\Delta = 0.3$ and $\delta = 0.045$, the projected EP position falls in a pronounced high η region, corresponding to the coexistence of the EP and UGR. Figure 4(b) plots η as a function of Δ for three δ values. For $\delta = 0.05$ and 0.053 , high η appears as sharp peaks near the two ends of the parameter range. By contrast, for $\delta = 0.045$, an additional broad peak appears near the EP position marked by the dashed line, indicating that this UGR is less sensitive to local perturbations of Δ . Figures 4(c) and 4(d) further show that the high η response of the UGR coexisting with the EP is maintained under variations of the ambient refractive index n_2 and the notch width parameter Δ . To clarify the role of the EP, Fig. 4(e) compares the UGR coexisting with the EP ($\Delta_0 = 0.3$) and the regular UGR not coexisting with an EP ($\Delta_0 = 0.125$) under Δ detuning. Here, Δ_0 is defined as the Δ value of the UGR at the maximum η in each case. The UGR coexisting with the EP maintains a broader high η response, while the regular UGR shows a narrower response and stronger parameter sensitivity. This comparison indicates that the enhanced tolerance is associated with the band region

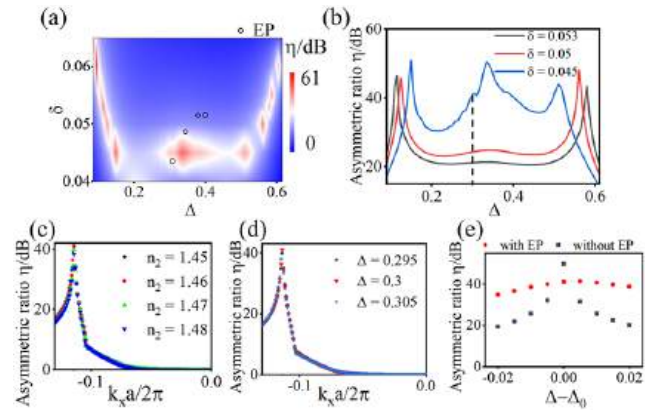


Fig. 4. (a) Distribution of η in the (Δ, δ) parameter space. Circles: EP positions. (b) η versus Δ for three δ values. (c), (d) η of the UGR coexisting with the EP under variations of n_2 and Δ , respectively. (e) Comparison between the UGR coexisting with the EP and a regular UGR under Δ detuning.

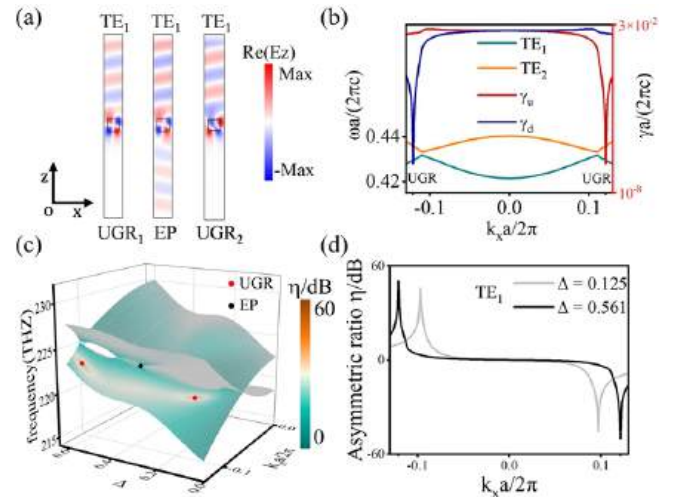


Fig. 5. (a) Electric field distributions of UGR₁, the EP, and UGR₂ on the TE₁ band. (b) Band structure around UGR₂, together with the upward and downward radiative decay rates. (c) Three dimensional band structure colored by η . (d) Comparison of η for UGR₁ and UGR₂.

delimited by the EP. The different responses to Δ and δ are also expected, since these two notch parameters affect the interband coupling strength and the radiation channel coefficients in different ways.

During tuning of the notch parameters, the EP and UGR usually appear at different parameter points, while the UGR migration path remains closely related to the EP distribution. When $\delta = 0.05$, the electric field distributions of UGR₁, the EP, and UGR₂ on the TE₁ band are shown in Fig. 5(a), at $\Delta = 0.125$, 0.335 , and 0.561 , with $k_x = -0.097$, -0.107 , and -0.121 , respectively. Figure 5(b) shows the radiative decay rates γ_u and γ_d and the band structure around the UGR at $\Delta = 0.561$. Figure 5(c) presents the three dimensional band structure mapped by the asymmetric radiation ratio η . As Δ increases, changes in interband coupling reconfigure the field profiles and radiation channel distributions of the hybridized modes, driving the UGR that satisfies the destructive interference condition in one

radiation channel to migrate along the TE_1 band from UGR_1 to UGR_2 through the critical coupling position marked by the EP. Figure 5(d) further shows that the UGRs mainly differ in their shifted positions, while high η is retained.

In summary, this work realizes the coexistence of a UGR and an EP in perturbed silicon nan gratings. The results show that UGRs and EPs are not isolated phenomena, but are linked through the same interband coupling process, which regulates both the complex band structure and the radiation channel distribution. At $\Delta = 0.3$ and $\delta = 0.045$, the UGR lies in the region delimited by the EP, where the nearly degenerate imaginary parts keep the radiative losses of the two modes close. This allows the UGR to remain stable over a finite parameter range rather than being confined to a single parameter point, with the asymmetric radiation ratio η maintained around 41 dB under variations of the notch width and changes in the ambient refractive index n_2 . Furthermore, tuning the notch parameters drives the UGR to migrate continuously in momentum space through the critical interband coupling position associated with the EP. This confirms that the EP marks the critical coupling position in the mode evolution, and that the UGR migration path is closely related to the EP distribution, thereby offering a route to designing robust unidirectional radiation devices.

Funding. National Natural Science Foundation of China (12274148, 12374347, 12174123); Natural Science Foundation of Guangdong Province (2025A1515012259); Special Projects in Key Fields of Ordinary Universities in Guangdong Province (New Generation Information Technology) (2023ZDZX1007).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results are not publicly available but may be obtained from the authors upon reasonable request.

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